Accelerated planetesimal growth in self-gravitating protoplanetary discs

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ABSTRACT

In the work presented here we consider the evolution of small planetesimals (radii ~ 1 - 10 metres) in marginally stable, self-gravitating protoplanetary discs. The drag force between the disc gas and the embedded planetesimals generally causes the planetesimals to drift inwards through the disc at a rate that depends on the particle size. In a marginally stable, self-gravitating disc, however, the planetesimals are significantly influenced by the non-axisymmetric spiral structures resulting from the growth of the gravitational instability. The drag force now causes the planetesimals to drift towards the peaks of the spiral arms where the density and pressure are highest. For small particles, that are strongly coupled to the disc gas, and for large particles, that have essentially decoupled from the disc gas, the effect is not particularly significant. Intermediate sized particles, which would generally have the largest radial drift rates, do, however, become significantly concentrated at the peaks of the spiral arms. These high density regions may persist for, of order, an orbital period and may attain densities comparable to that of the disc gas. Although at the end of the simulation only ~ 25 % of the planetesimal particles lie in regions of enhanced density, during the course of the simulation at least 75 % of the planetesimal particles have at some stage been in a such a region. We find that the concentration of particles in the spiral arms results in an increased collision rate, an effect that could significantly accelerate planetesimal growth. The density enhancements may also be sufficient for the growth of planetesimals through direct gravitational collapse. The interaction between small planetesimals and self-gravitating spiral structures may therefore play an important role in the formation of large planetesimals that will ultimately coagulate to form terrestrial planets or the cores of gas/ice giant planets.

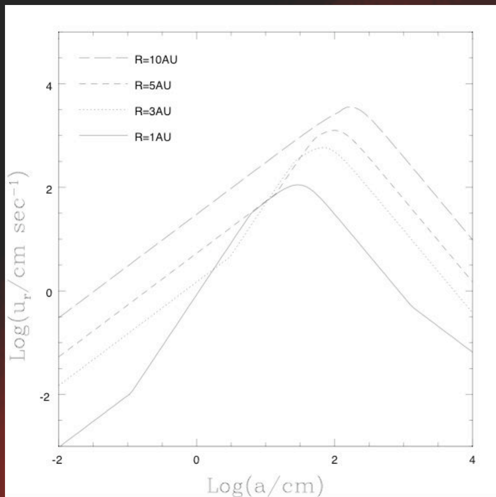


Figure 1. Radial velocity versus particle size at 4 different radii in an axisymmetric disc with properties similar to those considered here.

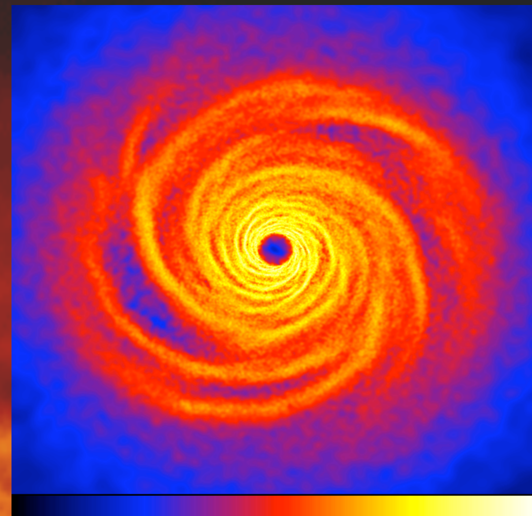


Figure 2. Surface density structure of a self-gravitating disc with a mass of $M_{\rm disc} = 0.25\, M_\odot$ around a star with a mass of $M_* = 1\, M_\odot$. The scale covers $1 < \log(\Sigma/{\rm g\,cm^{-2}}) < 4.7$.

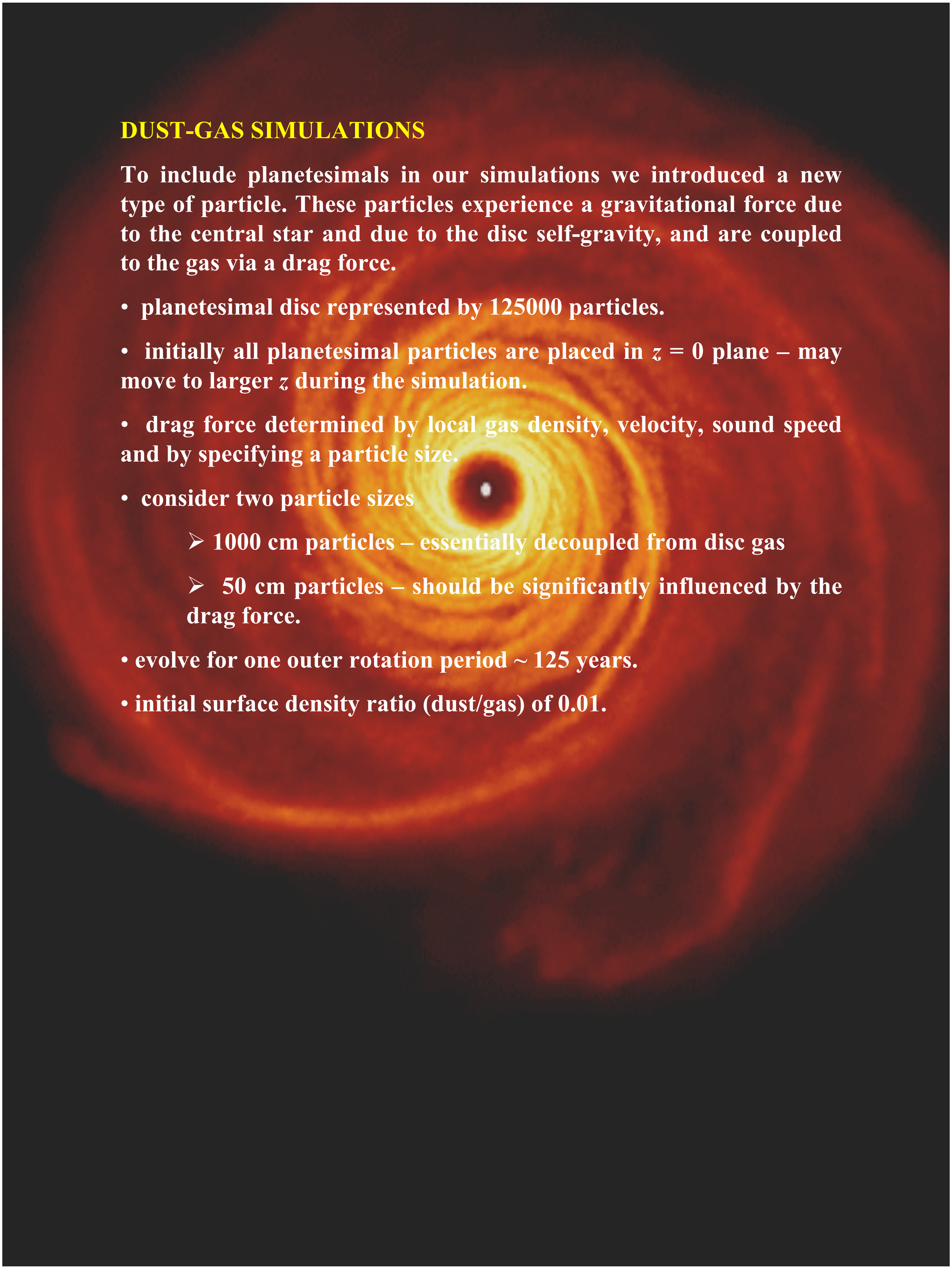
AXISYMMETRIC DISCS

In a "generic" protoplanetary disc, the pressure generally decreases with increasing radius and the pressure gradient therefore results in sub-Keplerian gas velocities. Dust grains or planetesimals are not influenced by the gas pressure and, in centrifugal equilibrium, therefore orbit with Keplerian velocities. The different gas and dust/planetesimal velocities result in a drag force (Whipple 1972; Weidenschilling 1977) that depends on the particle size. The effect of the drag force is to decelerate the dust/planetesimals, causing the particles to migrate in towards the central star. The migration rate depends on the particle size. Small particles are strongly coupled to the disc gas and hence migrate slowly. Large particles are essentially decoupled from the disc gas and also migrate slowly. There is, however, an intermediate size range for which the migration rate can be extremely large. Figure 1 shows the migration rate against particles size at 4 different radii for an axisymmetric disc with properties similar to the discs we will consider here.

SELF-GRAVITATING DISCS

In this work we consider the evolution of small planetesimals in marginally stable, self-gravitating discs. In a marginally stable disc (Gammie 2001; Rice et al. 2003; Lodato & Rice 2004) the disc quickly develops a spiral structure. In our simulations, this marginally stable state is achieved by imposing a cooling that is balanced by heating through the growth of the gravitational instability (Gammie 2001; Rice et al. 2003). Figure 1 shows the surface density structure of a self-gravitating disc with a mass of $M_{\rm disc} = 0.25\, M_\odot$ an outer radius of 25 au, orbiting a star with a mass of $M_* = 1\, M_\odot$. The simulation was carried out using Smoothed Particle Hydrodynamics (SPH) and the disc was modelled using 250000 particles.

The pressure gradient across the spiral arms changes from positive to negative and hence the gas velocities change from super- to sub-Keplerian. The drag force will therefore cause dust/planetesimals to migrate towards the center of the spiral arms where the pressure gradient is zero (Haghighipour & Boss 2003). This is likely to have the largest effect on particles that have the largest migration rates (see Figure 1).



DUST-GAS SIMULATIONS

To include planetesimals in our simulations we introduced a new type of particle. These particles experience a gravitational force due to the central star and due to the disc self-gravity, and are coupled to the gas via a drag force.

- **planetesimal disc represented by 125000 particles.**
- **initially all planetesimal particles are placed in $z = 0$ plane – may move to larger z during the simulation.**
- **drag force determined by local gas density, velocity, sound speed and by specifying a particle size.**
- **consider two particle sizes**
  - **1000 cm particles – essentially decoupled from disc gas**
  - **50 cm particles – should be significantly influenced by the drag force.**
- **evolve for one outer rotation period ~ 125 years.**
- **initial surface density ratio (dust/gas) of 0.01.**

RESULTS

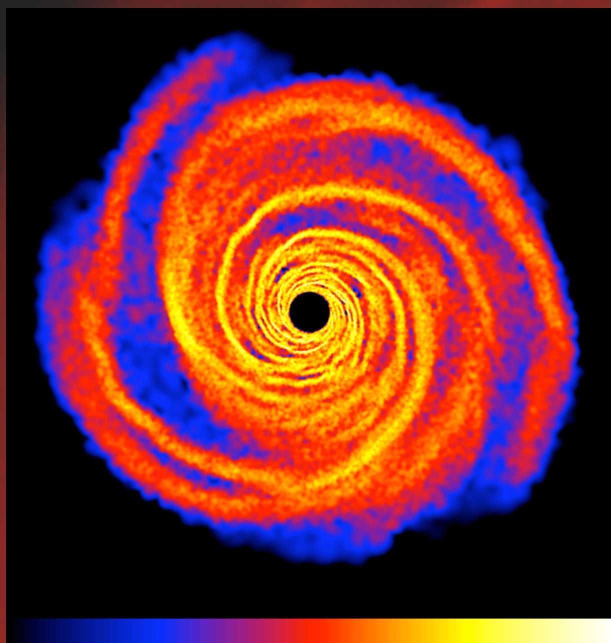


Figure 3. Surface density structure of 1000 cm particles embedded in the disc gas. To compare the structure in the particle disc with that of the gas disc, the surface density has been multiplied by 100 and the colour scale is the same as in Figure 2.

1000 cm particles

For the disc properties considered here, the 1000 cm particles are essentially decoupled from the disc gas. The drag force therefore does not play an important role in their evolution and the particles are influence primarily by the gravitational potential. The structure in the 1000 cm particle disc is therefore very similar to the structure in the gas disc (Figure 2).

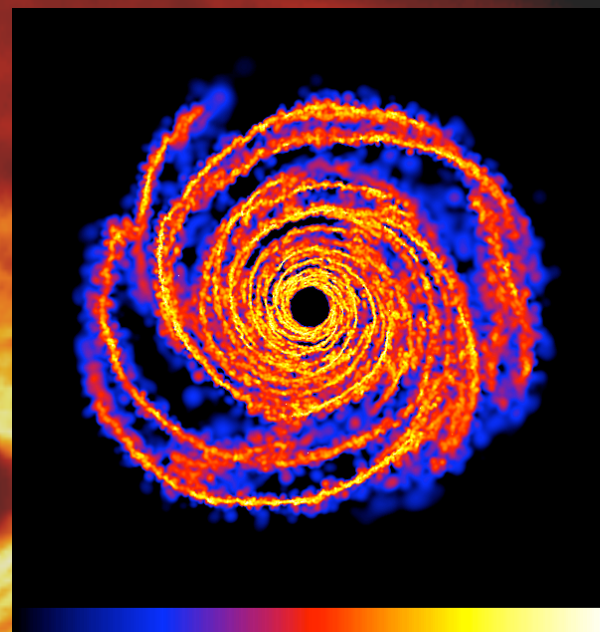
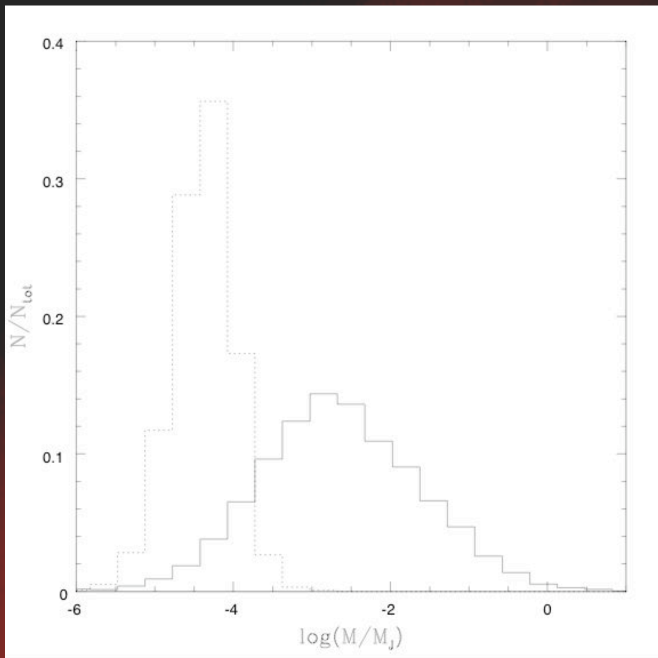


Figure 4. Surface density structure of 50 cm particles embedded in the disc gas. The surface density has been scaled in the same way as in Figure 3.

50 cm particles

For the disc properties considered here, 50 cm particles are strongly influenced by the drag force (see Figure 1). They therefore become strongly concentrated in the center of the spiral arms where the pressure gradient is zero. The density of these particles can be enhanced by as much as a factor of 100, achieving densities similar to that of the disc gas (assuming an initial surface density ratio of 0.01). We also find that these high density regions may persist for of order an orbital period.



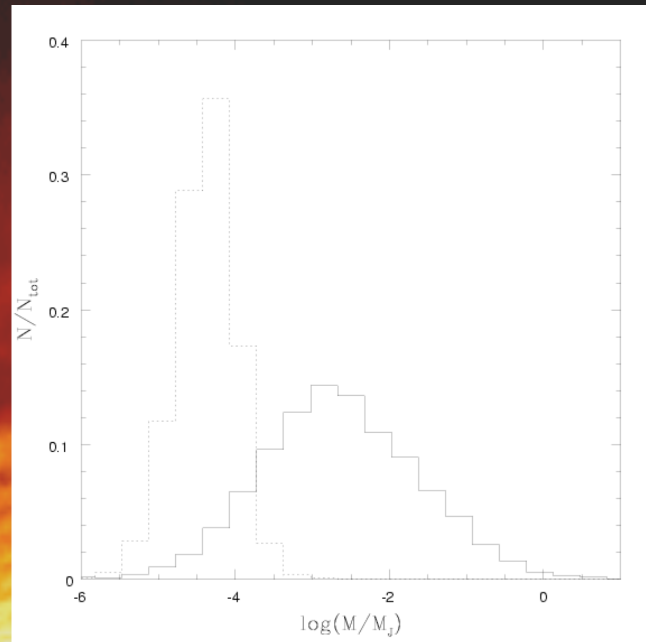


Figure 5. Distribution of collision rates, relative to a mean collision rate from a simulation in which the drag force was ignored. The solid line is for the 50 cm simulation, the dashed line is for the 1000 cm simulation, and the dotted line is for the reference simulation in which the drag force was ignored.

Figure 6. Distribution of M/M_J where M is the minimum resolvable mass (mass within 2 smoothing lengths) and M_J is the local Jeans mass. Values of M/M_J close to unity suggest the self-gravity in the particle disc may play a role in its evolution.

Collision rate

In a simulation in which the drag force was neglected (dotted line in Figure 5) the density enhancements due to the self-gravitating spiral structures can increase the collision rate slightly. Including the drag force can increase the collision rate significantly, especially for particles that become strongly concentrated at the center of the spiral arms (solid line in Figure 5). Although we don't know how well particles of this size stick together, this increase in collision rate should lead to accelerated planetesimal growth.

Jeans mass

A planetesimal surface density enhancement of a factor of ~ 20 may be sufficient to make the planetesimal sub-disc self-gravitating (Youdin & Shu 2002). This is precisely the enhancments that are achieved in the simulation using 50 cm particles. We do not, however, include the self-gravity of the planetesimals and hence cannot determine if their self-gravity becomes important. We can, however, compare the minimum resolvable mass in the planetesimal disc (mass within 2 smoothing lengths of every SPH planetesimal particle) with the local Jeans mass. For the 50 cm simulation this ratio can be of order unity, suggesting that self-gravity in the planetesimal sub-disc will indeed become important.

CONCLUSIONS

In this work we have examined how the interaction between a self-gravitating gaseous protoplanetary disc, and embedded planetesimals may accelerate planetesimal growth.

- Particles that are largely decoupled from the disc gas are not strongly influenced by the drag force.
- Particles that would normally experience the fastest migration may become concentrated in the center of the spiral arms and may achieve densities comparable to the disc gas (this does depend on what fraction of the total planetesimal mass is contained within the size range where this effect is important).
- In the regions where the density is enhanced, the collision rate can increase by up to two orders of magnitude, potentially accelerating planetesimal growth.
- The density enhancements may also be sufficient for planetesimal growth through direct gravitational collapse. Comparisons between the Jeans mass and the minimum resolvable mass in the simulation in which the planetesimals become concentrated in the spiral arms, suggest that the planetesimal self-gravity may indeed become important.

REFERENCES

Gammie C.F., 2001, ApJ, 553, 174.

Haghighipour N., Boss A.P., 2003, ApJ, 583, 996.

Lodato G., Rice W.K.M., 2004, MNRAS, 351, 630.

Rice W.K.M., Armitage P.J., Bate M.R. & Bonnell I.A., 2003, MNRAS, 339, 1025.

Weidenschilling S., 1977, MNRAS, 180, 57.

Whipple F.L., 1972, in Elvius A., ed., From Plasma to Planets, Wiley, London.

Youdin A.N., Shu F.H., 2002, ApJ, 580, 494

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